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(54) **Method of controlling a variable cooling capacity compressor and refrigerator or freezer controlled by such method**

(57) A method for controlling the cooling capacity of a variable cooling capacity (VCC) compressor of a refrigerator or freezer (R) comprises an electronic controller (C) which receives a temperature feedback signal from the refrigerator/ freezer cell. The output signal of the electronic controller is based on a predetermined on/ off band which is different from the on/off temperature band and which is preferably a on/off speed band.

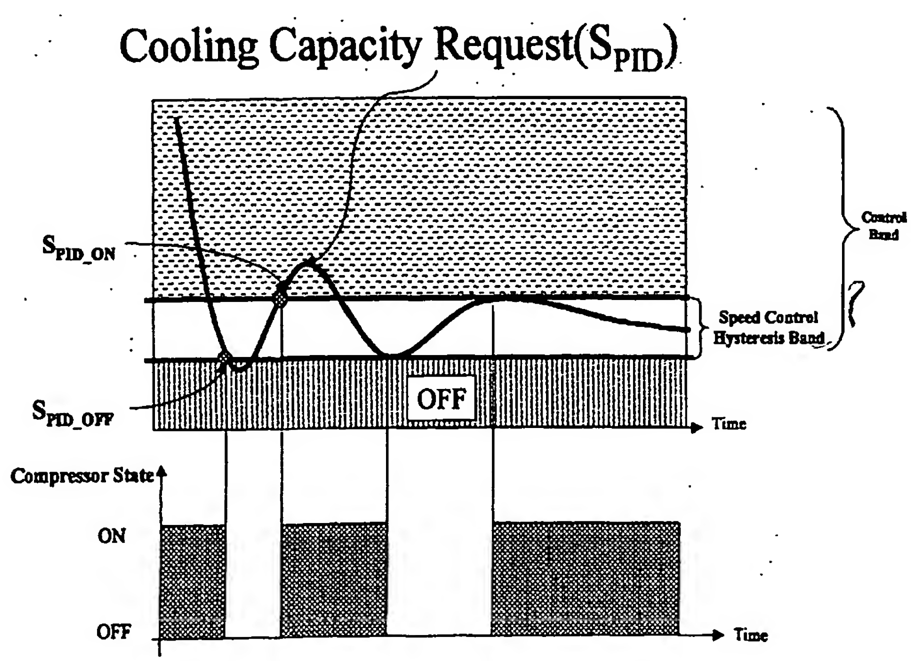

Fig. 4

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Description

[0001] The present invention relates to a method of controlling the power output of variable cooling capacity compressor of a refrigerator/freezer with an electronic controller that receives a temperature feedback signal from the refrigerator/freezer. With the term "variable cooling capacity" we mean all kinds of compressors which can vary either the motor speed (variable speed compressors) or the displacement of the compressor (linear compressors). In the first case the power output of the compressor is proportional to the motor speed, which is the feature actually controlled. In the second case the power output is proportional to the stroke of the piston of the compressor, which is the feature actually controlled.

[0002] The present inventions refers also to a new method of controlling the temperature of a refrigerator/freezer cell in which the traditional method based on temperature hysteresis (error proportional part) is replaced by a new and more efficient one.

[0003] The temperature control of a freezer or a refrigerator is usually obtained, in case of a fixed or variable cooling capacity (VCC) compressor, by cycling the ON/OFF compressor state, by means of a so-called "hysteresis" or relay control. An example of the mentioned control is expressed by the following control process: if the temperature to be controlled is less than x°C, then the compressor is switched OFF (because the temperature inside the cell of the refrigerator or freezer is too low); if temperature is greater than y°C, then the compressor is switched ON (because the temperature inside the cell is too high). The x and y values are two predetermined temperatures linked to the set temperature and the difference (y-x) defines the temperature hysteresis range.

[0004] The effect of the hysteresis or relay control is that the cabinet temperature (refrigerator or freezer) is forced to oscillate from a minimum to a maximum temperature value and so the food is never at constant temperature.

[0005] If x value is very close to y value (low hysteresis value), frequent ON/OFF cycles will be obtained. The consequence is a noise production and an increase of energy consumption.

[0006] The oscillation amplitude of the cell temperature is not controlled because it depends on the load amount and type (thermal inertia) and from the external temperature too. For instance after the compressor has been set to ON (OFF), the temperature continues to decrease (increase) by inertia. The main consequence of this is a limited control of the food preservation because of the dependency of the load thermal inertia.

[0007] The ON/OFF temperature control technique, commonly implemented in appliances where a usual ON/OFF compressor is installed, is also used in cases in which the compressor has a variable cooling capacity such as variable speed compressors, or linear compressors. There are several reasons for adopting this ON/OFF temperature hysteresis control and the main reasons are:

1) it is convenient, from the energy point of view, to switch OFF the compressor instead of running it with the minimum cooling capacity (minimum speed),
2) by running the compressor at the minimum cooling capacity the temperature to be controlled may be cooler than the required so that the compressor OFF state is preferred.
It is well known that a continuous control is performing better than ON/OFF control: the peaks of current during the motor-compressor starting phase are eliminated and, in the refrigeration field, the energy spent to compensate the pressure losses is reduced as well.

[0008] One of the purposes of the invention is thus to develop a control method and a control arrangement for a VCC compressor having a lower energy consumption than the controls known from the state of the art.

[0009] According to the invention, this is done by setting the compressor with the output signal of the electronic controller that is based on a predetermined on/off band different from the usual on/off temperature band. If a variable speed compressor is used, the output signal of the electronic controller is based on a predetermined on/off speed band. If a linear compressor is used, the output signal of the electronic controller is based on a predetermined on/off displacement band.

[0010] The applicant has discovered that by using a reference variable in the temperature control loop which takes into account also other parts of the temperature error, as the integrative and/or derivative error parts, a surprising reduction in energy consumption can be obtained, i.e. up to 5% if compared to a traditional temperature hysteresis control. The effect is that the OFF condition is no longer dependent from a fixed temperature value but it depends also by the past (integrative) and future (derivative) parts of the error. A part from the advantage of a high energy saving, with the method according to the invention it is possible to have additional benefits in term of a more stable temperature and noise reduction due to the decrease or elimination of ON/OFF cycles.

[0011] In the following the invention is described on the basis of the following figures:

- figure 1 shows a known time/temperature diagram used for a typical control strategy for variable cooling capacity compressors;
- figure 2 is a schematic view of the control loop according to one embodiment of the invention in which the VCC (Variable Cooling Capacity) compressor is represented by a variable speed compressor (compressor that changes the cooling capacity accord-

ing to an input reference speed) and a so called hybrid controller is composed by a regulator system (i.e. PID control whose purpose is to set the suitable compressor speed) and by a cooling capacity adapter block;

- figures 3a and 3b are schematic block diagrams showing the control method according to the invention;
- figure 4 shows a time/speed diagram according to the control technique of figure 2 based on the speed control variable;
- figure 5 is a diagram showing the control behavior of the known control method for a freezer according to the control strategy of figure 1, in which different target temperatures are set; and
- figure 6 is a diagram similar to figure 4 showing the control behavior of the control method according to the invention.

[0012] In the prior art control method shown in figure 1 the temperature low band T_{LB} establishes the temperature value for switching OFF the compressor. T_{ON} determines the ON condition while the T_{UB} can be used to force the maximum cooling capacity in case of very hot cell or cabinet temperature condition.

[0013] Between T_{LB} and T_{UB} a regulator system (i.e. PID or a "Fuzzy Logic" control in which the temperature error and/or derivative of the error are used as input signals) can compute the proper cooling request in a predetermined temperature control band.

[0014] In fig. 5 the temperature control behavior is shown when a method according to figure 1 is adopted and when different target temperatures are set. The temperature hysteresis value of this example is 0,5 °C. In the diagram the compressor speed S (rpm) is plotted (upper part) together with the set temperature T or the actual cell temperature A (lower part of the diagram). From the diagram, every time the actual temperature is below the target temperature by 0.5°C, the compressor is switched OFF and the Compressor Speed is set to 0 (zero) rpm.

[0015] In figure 2 a temperature control loop is shown in which the ON/OFF compressor condition is not determined by the temperature hysteresis control but, according to the present invention, it is determined by a hybrid control based on a cooling capacity request hysteresis control.

[0016] To control the cabinet temperature, a regulator system C, PID like, is used. In figure 2 a variable cooling capacity compressor, represented by a variable speed compressor VSC, is shown together with a refrigerator R and a temperature probe P inside the cell of the refrigerator.

[0017] The regulator system C sets the proper cooling capacity to the compressor up to reduce the error temperature close to 0 °C. i.e. actual temperature = target temperature.

[0018] The compressor speed "u" is in the example the output variable of the regulator system block C. The block K, defined cooling capacity adapter, receives the compressor speed computed by the regulator system as input and, within it, the speed hysteresis control is implemented. The output of K block is the compressor state (ON or OFF state) and, in case of ON state, a compressor speed "u*" within a certain range value. Usually the compressor speed range is limited: i.e. 4000rpm (maximum) and 2000rpm (minimum). The low and high limits depend from motor construction (mechanical and electrical specifications).

[0019] In Fig. 4 the control technique according to the control loop of figure 2 is shown. The ON/OFF speed band substitutes the ON/OFF temperature band. The OFF speed value S_{PID_OFF} ,according to the temperature control loop, is preferably lower than the minimum compressor speed=2000rpm. The OFF condition is obtained by comparing the regulator's output parameter, $u=S_{PID}$, with a predetermined value: if the $S_{PID} <=$ Speed_OFF then the adapter K switches OFF the compressor. In the example of figure 4 a hysteresis of 400 rpm is used. The compressor is again switched ON only when the S_{PID} becomes higher than a determined value Speed_ON, i.e. 2000 rpm. The above control technique is also shown in the block diagram of figures 3a and 3b.

[0020] Referring to figure 3a, the first step is to read both the temperature of the sensor P in the cell and the target temperature fixed by the user. At step 2, an assessment of the error is made at present time t_0 and at previous times t_1 and t_2. At step 3 the incremental cooling capacity, which is due to the proportional part of the error, is calculated. At step 4, the incremental cooling capacity, which is due to the derivative part of the error, is calculated. At step 5, the incremental cooling capacity, which is due to the integral part of the error, is calculated. At step 6 the sum of the above three components is calculated. At step 7 the new request of cooling capacity is calculated by the controller. At step 8 the previous state of the compressor is stored: OFF_state = compressor switched off, ON_state = compressor switched on. At step 9, if the new request of cooling capacity is considered too low (i.e. lower than a predetermined value Speed_OFF), then the compressor is given a state off (OFF_state). At step 10, if the new request of cooling capacity is higher than the re-switching threshold speed_on, then the compressor is given a state on (ON_state). At step 11, if the compressor passes from OFF_state to ON_state, a new request of cooling capacity is given: Reset_Cooling_Capacity. This is a predetermined value on which the control system restarts the control loop when the compressor is switched on. A preferred strategy for further reducing energy consumption is to select the reset value as the value corresponding to minimum cooling capacity (minimum speed).

[0021] Referring to figure 3b, step 12 corresponds to the limitation of the control action to the maximum allowed (maximum speed). Step 13 corresponds to the limitation of the control action to the minimum that is al-

lowed without switching off the compressor. At step 14 the cooling capacity difference between the new request fixed by the controller and the present request actually carried out by the compressor is assessed. At step 15 the variable Actual_Cooling_Capacity is given the request change. Step 16 corresponds to a lower limitation for the cooling capacity; this is due to certain technical limitations of variable speed compressors that, at very low speed, do not guarantee a proper lubrication. Step 17 corresponds to an upper limitation of cooling capacity and step 18 is a final check of the state of the compressor in order to decide if it is switched on or switched off. Of course at the end of the above control flow a new control cycle starts with the same flow pattern.

[0022] The $u=S_{PID}$ is a value which is used for controlling purposes and it may not correspond to the actual cooling capacity inputted to the compressor u*.

[0023] When the compressor passes from the OFF to the ON state, the u control parameter of the regulator system is set to a convenient predetermined value: Reset_Cooling _Capacity. For energy saving purposes and for temperature control stability reasons the Reset_Cooling _Capacity value is set to the minimum cooling capacity of the compressor.

[0024] Figure 6 shows the advantages of the method according to the invention. One of such advantages is that temperature oscillation is strongly reduced because the number of cycles is reduced or even said cycles are eliminated. This is possible since the compressor speed, determined by the regulator system C (i.e. PID), takes into account the proportional part of the error as well the derivative and integrative parts. All these components make the control able to compensate the temperature error by its present, past and future error state. The u control parameter includes all or some of the above mentioned information and not only the proportional part as the conventional control does by switching the compressor OFF when the temperature is below to a threshold value. The present invention makes use of a hybrid control system able to reduce the cooling capacity request up to reach the minimum admitted value ad set this value to the compressor. In cases in which the cell or cabinet temperature continues to decrease the OFF condition is obtained only when the u control parameter is below a certain threshold vale.

[0025] From a comparison of figures 5 and 6 it is evident that with the control method according to the invention the OFF conditions occur only when it is strictly necessary (high target temperature and/or low room temperature), while in all the other conditions the system has "time" to find a stable cooling capacity (i.e.speed) able to keep the foods at constant temperature.

Claims

1. Method for controlling the cooling capacity of a variable cooling capacity (VCC) compressor of a refrigerator or freezer (R) with an electronic controller (C) which receives a temperature feedback signal, **characterized in that** the output signal of the electronic controller is based on a predetermined on/off band which is different from the on/off temperature band.

2. Method according to claim 1, in which the cooling capacity compressor is a variable speed compressor (VSC), **characterized in that** the output signal of the electronic controller is a speed signal based on a predetermined on/off speed band.

3. Method according to claim 1, in which the cooling capacity compressor is a linear compressor, **characterized in that** the output signal of the electronic controller is a piston stroke signal based on a predetermined on/off piston stroke band.

4. Method according to claim 2, **characterized in that** the low end of the on/off speed band is lower than or equal to the minimum speed of the compressor (VSC).

5. Method according to claim 2 or 4, **characterized in that** the high end of the on/off speed band is higher than or equal to the minimum speed of the compressor (VSC).

6. Method according to any of the preceding claims, **characterized in that** the temperature feedback signal is issued by a temperature sensor (P) placed in a refrigeration cell of the refrigerator or freezer (R).

7. Method according to any of the preceding claims, **characterized in that** the electronic controller (C) is selected in the group consisting of proportional-integral (PI) controller, proportional-derivative (PD) controller, proportional-integral-derivative (PID) controller and any fuzzy logic controller in which the temperature error and/or derivative of the error are used as input signals.

8. Method according to claim 2, **characterized in that** when the electronic controller switches on the compressor, it is always switched on at the minimum speed.

9. Refrigerator or freezer having a refrigeration cell and a variable cooling capacity (VCC) compressor with an electronic controller (C) which receives a temperature feedback signal from a temperature sensor (P) placed in said cell, **characterized in that** the electronic controller (C) is able to provide the variable cooling capacity compressor (VCC) with a signal that is based on a predetermined on/off band which is different from the on/off temperature band.

10. Refrigerator or freezer according to claim 9 in which the cooling capacity compressor is a variable speed compressor (VSC), **characterized in that** the output signal of the electronic controller is a speed signal based on a predetermined on/off speed band.

11. Refrigerator or freezer according to claim 9 in which the cooling capacity compressor is a linear compressor, **characterized in that** the output signal of the electronic controller is a piston stroke signal based on a predetermined on/off piston stroke band.

12. Refrigerator or freezer according to claim 10, **characterized in that** the low end of the on/off speed band is lower than or equal to the minimum speed of the compressor (VSC).

13. Refrigerator or freezer according to claim 10 or 12, **characterized in that** the high end of the on/off speed band is higher than or equal to the minimum speed of the compressor (VSC).

14. Refrigerator or freezer according to any of claims 9 - 13, **characterized in that** the electronic controller (C) is selected in the group consisting of proportional-integral (PI) controller, proportional-derivative (PD) controller, proportional-integral-derivative (PID) controller and fuzzy logic controller.

15. Refrigerator or freezer according to any of claims 9 - 13, **characterized in that** when the electronic controller switches on the compressor, it is always switched on at the minimum speed.

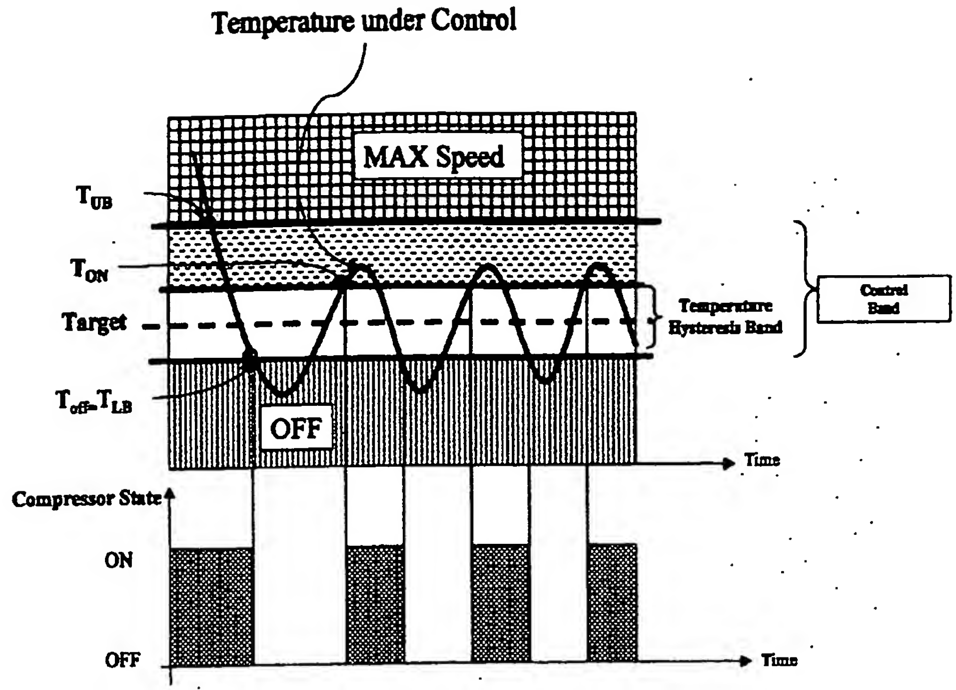
Temperature under Control
MAX Speed
T_{UB}
T_{ON}
Target
$T_{off}=T_{LB}$
OFF
Temperature Hysteresis Band
Control Band
Time
Compressor State
ON
OFF
Time

Fig. 1

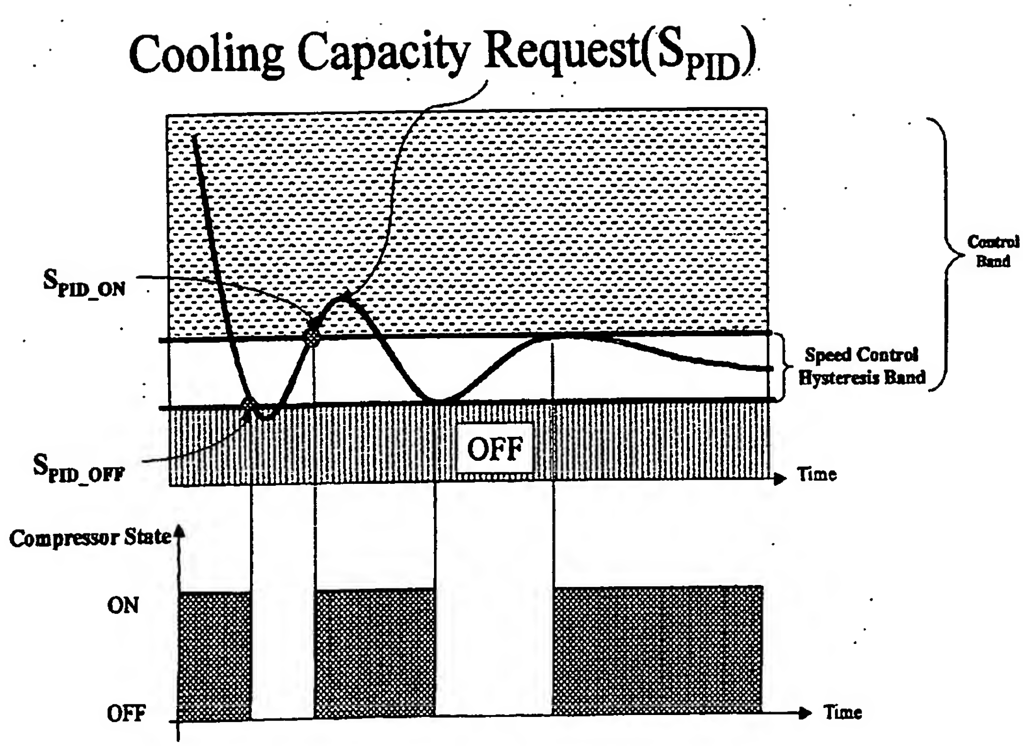
Cooling Capacity Request(S_{PID})
S_{PID_ON}
S_{PID_OFF}
OFF
Control Band
Speed Control Hysteresis Band
Time
Compressor State
ON
OFF
Time

Fig. 4

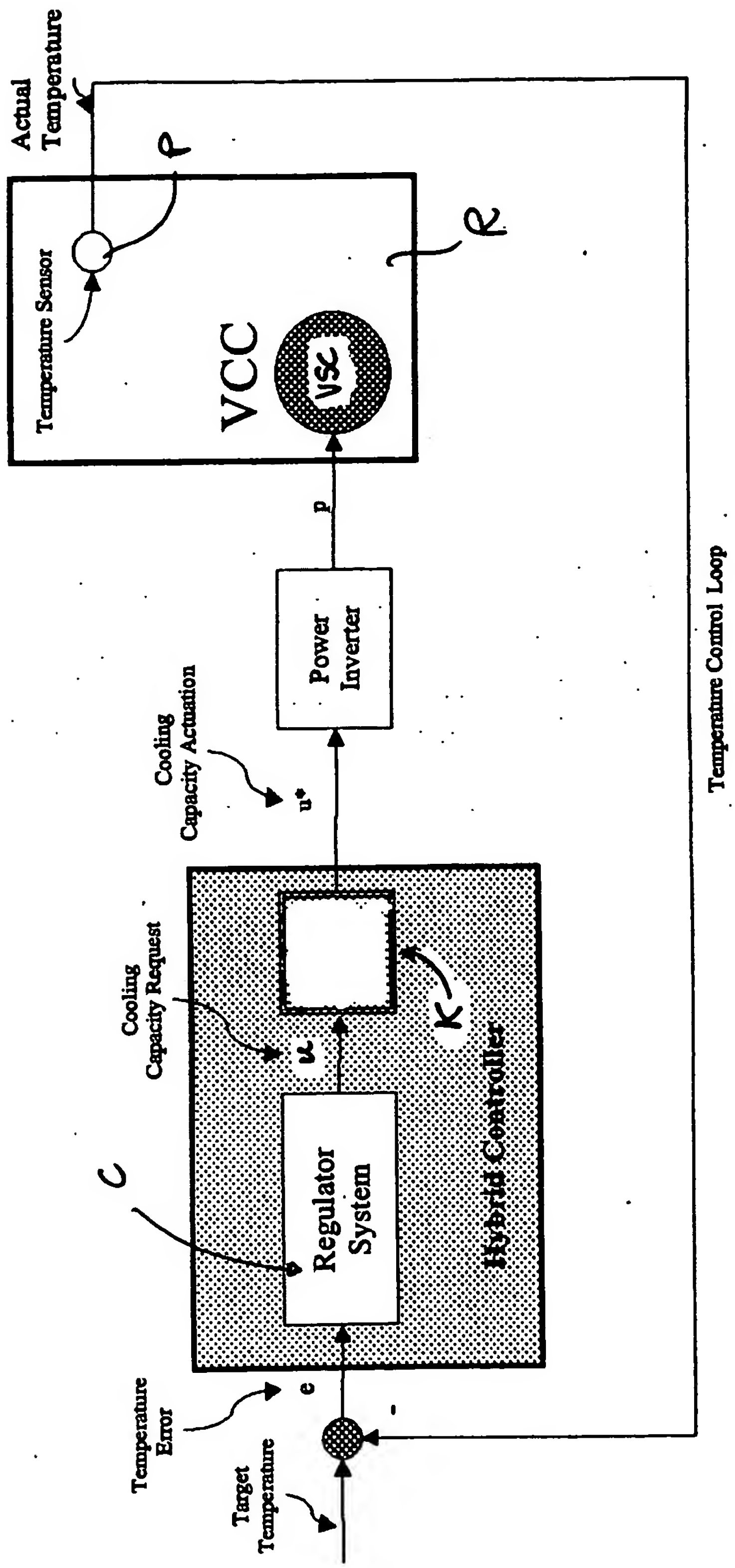
Actual Temperature
P
Temperature Sensor
R
VCC
VSC
p
Power Inverter
Cooling Capacity Actuation
u*
Cooling Capacity Request
u
K
C
Regulator System
Hybrid Controller
Temperature Error
e
-
Target Temperature
Temperature Control Loop

Fig. 2

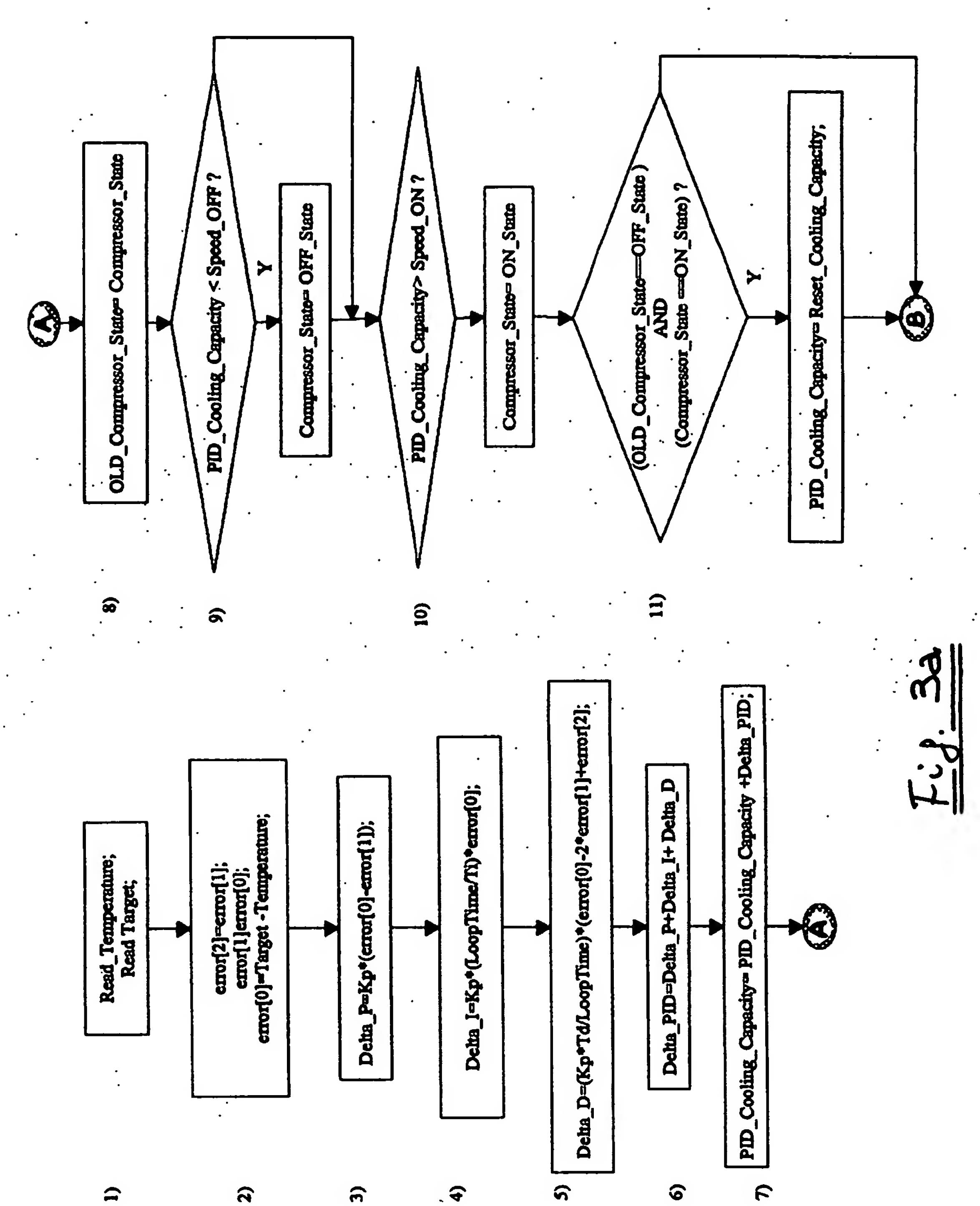
1)
Read_Temperature;
Read Target;
2)
error[2]=error[1];
error[1]=error[0];
error[0]=Target -Temperature;
3)
Delta_P=Kp*(error[0]-error[1]);
4)
Delta_I=Kp*(LoopTime/Ti)*error[0];
5)
Delta_D=(Kp*Td/LoopTime)*(error[0]-2*error[1]+error[2];
6)
Delta_PID=Delta_P+Delta_I+ Delta_D
7)
PID_Cooling_Capacity= PID_Cooling_Capacity +Delta_PID;
A
A
8)
OLD_Compressor_State= Compressor_State
9)
PID_Cooling_Capacity < Speed_OFF ?
Y
Compressor_State= OFF_State
10)
PID_Cooling_Capacity> Speed_ON ?
Compressor_State= ON_State
11)
(OLD_Compressor_State==OFF_State)
AND
(Compressor_State ==ON_State) ?
Y
PID_Cooling_Capacity= Reset_Cooling_Capacity;
B

Fig. 3a

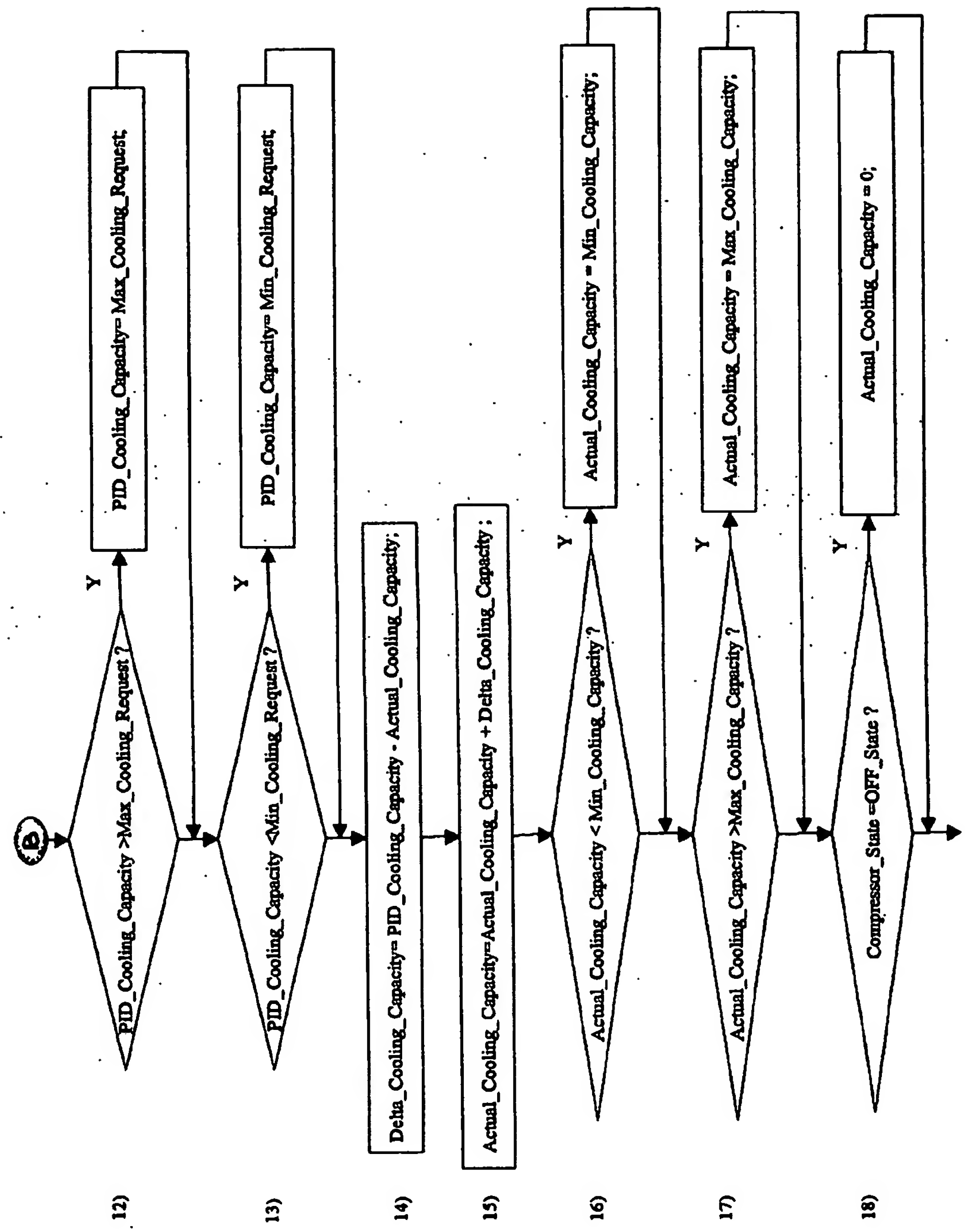
12)
PID_Cooling_Capacity >Max_Cooling_Request ?
Y
PID_Cooling_Capacity= Max_Cooling_Request;
13)
PID_Cooling_Capacity <Min_Cooling_Request ?
Y
PID_Cooling_Capacity= Min_Cooling_Request;
14)
Delta_Cooling_Capacity= PID_Cooling_Capacity - Actual_Cooling_Capacity;
15)
Actual_Cooling_Capacity=Actual_Cooling_Capacity + Delta_Cooling_Capacity ;
16)
Actual_Cooling_Capacity < Min_Cooling_Capacity ?
Y
Actual_Cooling_Capacity = Min_Cooling_Capacity;
17)
Actual_Cooling_Capacity >Max_Cooling_Capacity ?
Y
Actual_Cooling_Capacity = Max_Cooling_Capacity;
18)
Compressor_State =OFF_State ?
Y
Actual_Cooling_Capacity = 0;

Fig. 3b

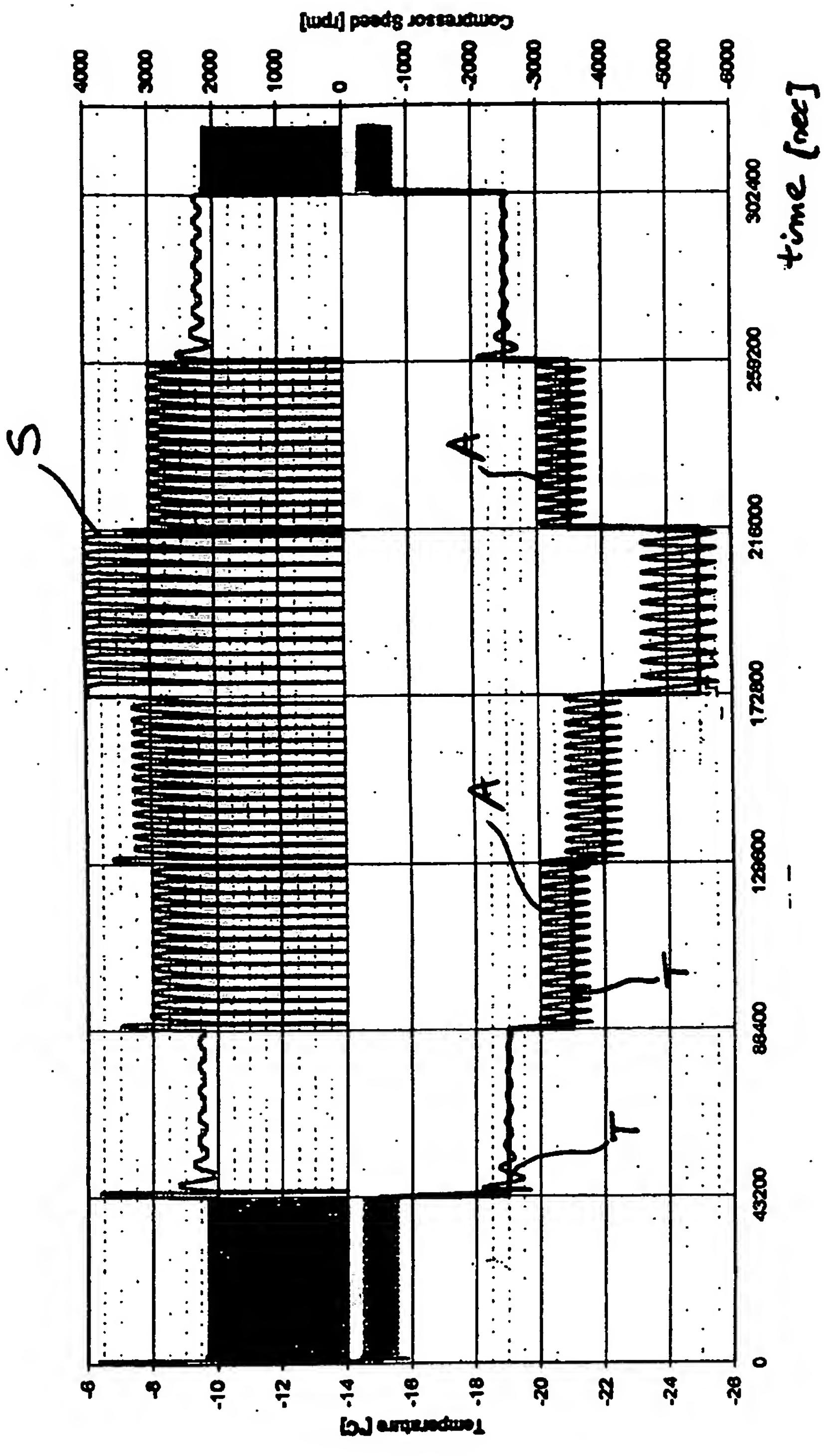
Compressor Speed [rpm]
Temperature [°C]
time [sec]
S
A
A
T
T
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
0
43200
86400
129600
172800
216000
259200
302400

Fig. 5

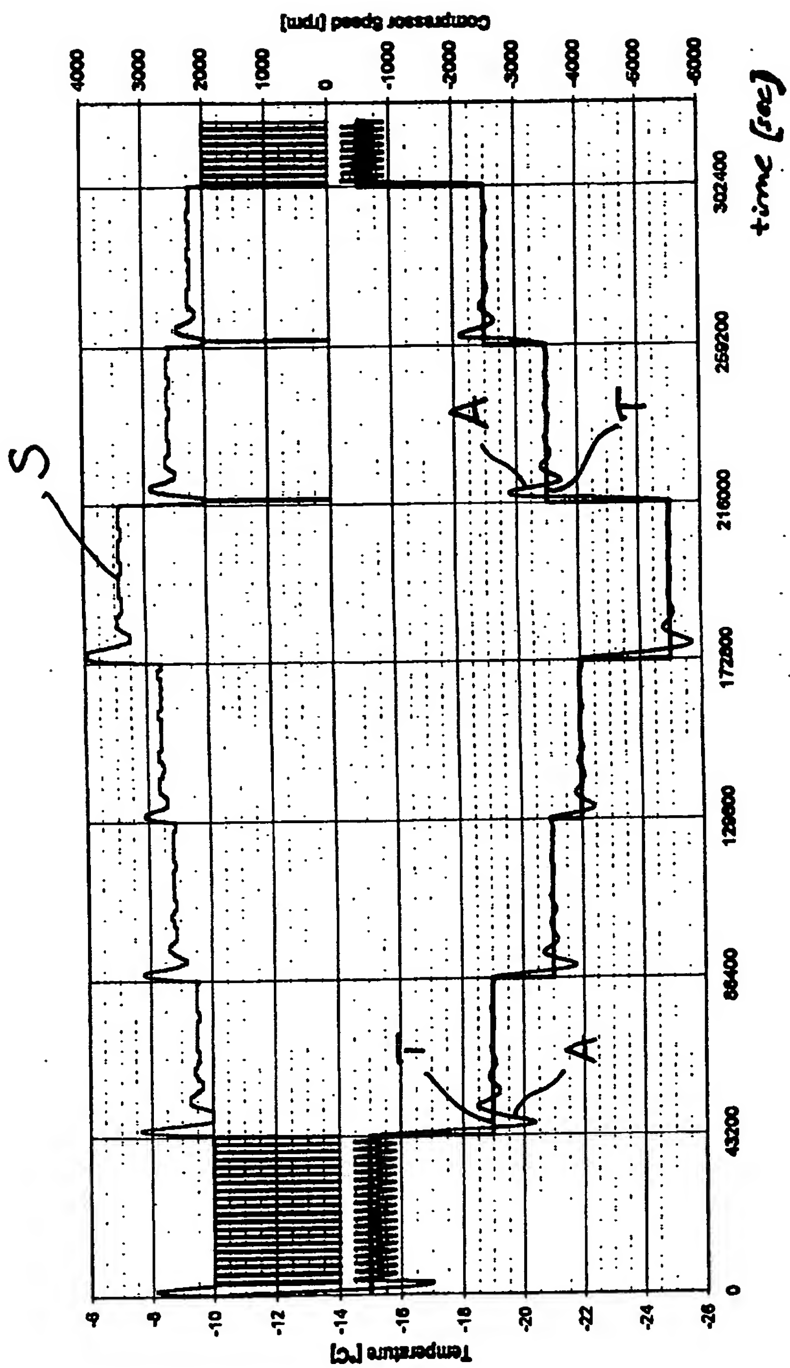
Compressor Speed [rpm]
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
time [sec]
0
43200
86400
129600
172800
216000
259200
302400
Temperature [°C]
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
S
A
T
T
A

Fig. 6

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EUROPEAN SEARCH REPORT

Application Number
EP 01 12 8455

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	25 April 2002	Busuiocescu, B

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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A : technological background
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EUROPEAN SEARCH REPORT

Application Number
EP 01 12 8455

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
A	US 4 934 157 A (SUZUKI SHINICHI ET AL) 19 June 1990 (1990-06-19) * the whole document *		

TECHNICAL FIELDS SEARCHED (Int.Cl.7)

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D : document cited in the application
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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 01 12 8455

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82